

Degenerate versus semi-degenerate transport in a correlated 2D hole system

Richard L.J. Qiu,¹ Xuan P. A. Gao,^{1,*} Loren N. Pfeiffer,² and Ken W. West²

¹*Department of Physics, Case Western Reserve University, Cleveland, OH 44106*

²*Department of Electrical Engineering, Princeton University, Princeton, NJ 08544*

(Dated: January 20, 2013)

It has been puzzling that the resistivity of high mobility two-dimensional(2D) carrier systems in semiconductors with low carrier density often exhibits a large increase followed by a decrease when the temperature (T) is raised above a characteristic temperature comparable with the Fermi temperature (T_F). We find that the metallic 2D hole system (2DHS) in GaAs quantum well (QW) has a linear density (p) dependent conductivity, $\sigma \approx e\mu^*(p - p_0)$, in both the degenerate ($T \ll T_F$) and semi-degenerate ($T \sim T_F$) regimes. The T -dependence of $\sigma(p)$ suggests that the metallic conduction ($d\sigma/dT < 0$) at low T is associated with the increase in μ^* , the effective mobility of itinerant carriers. However, the resistivity decrease in the semi-degenerate regime ($T > T_F$) is originated from the reduced p_0 , the density of immobile carriers in a two-phase picture.

PACS numbers: 71.30.+h, 73.40.-c, 73.63.Hs

The electron transport in 2D electron systems has been a research focus for long time[1]. A pioneering work on the one-parameter scaling theory of localization [2] concluded that all non-interacting disordered 2D electronic systems have to be localized in zero magnetic field ($B=0$). The application of the celebrated scaling theory of localization and the Fermi liquid (FL) model in strongly interacting 2D systems, however, was questioned by a number of experimental observations of an apparent metallic state and metal-insulator transition (MIT) in various 2D electron or hole systems with low density and high mobility [3]. Although low carrier density implies a large value of r_s (the ratio between Coulomb potential energy and kinetic energy) or strong correlation effects, different opinions exist on how the strong correlations affect the carrier transport in dilute 2D systems and what mechanism causes the metallic transport [4–12].

After extensive experimental studies of transport in various dilute 2D carrier systems in semiconductors, one salient feature stands out in the 2D metallic transport phenomena. For densities above the critical density p_c , the temperature dependent resistivity $\rho(T)$ is often non-monotonic: ρ first increases and then decreases as the temperature is raised above a characteristic temperature $T^* \sim T_F$. Such non-monotonic behavior in $\rho(T)$ when low density 2D system becomes semi-degenerate has been observed in all the three most widely studied systems: n-Si [13, 14], p-GaAs [15–17] and n-GaAs [18]. This sign change in $d\rho/dT$ at T^* is generic for the 2D metallic state if the phonon scattering contribution to resistivity does not overwhelm the impurity-scattering induced ρ in the semi-degenerate regime [16, 19]. The existence of a non-monotonic $\rho(T)$ is essential in many leading theoretical explanations for the 2D metallic state [7–9, 12]. Therefore, to further distinguish the mechanisms of the 2D metallic state, it would be desirable to address exper-

imentally the transport and scattering processes as the system crosses over from degenerate ($T \ll T_F$) to semi-degenerate ($T \sim T_F$) regime. In addition, transport of 2D electron fluids with $r_s \gg 1$ in the semi-degenerate regime is interesting in its own right. In this seldom studied regime, non-Boltzmann type transport like hydrodynamics may play an important role [9, 20].

Here we compare the density dependence of conductivity in the degenerate and semi-degenerate regimes for a low density 2DHS with strong interactions ($r_s > 18$ for the densities covered in this experiment [21]). In the metallic state, our 2DHS in 10nm wide GaAs QWs exhibits a pronounced non-monotonic $\rho(T)$ associated with the degenerate to semi-degenerate crossover and a strong low T metallicity[17, 22], due to the stronger confinement and smaller phonon scattering contribution to the resistivity in narrow QWs[16, 17, 19]. The particular focus of this paper is on understanding the non-monotonic $\rho(T)$ of correlated 2DHS from the temperature dependence of $\sigma(p)$ in the *high conductivity regime* ($\sigma \gg e^2/h$). In such metallic regime away from the critical point of MIT, we find that the conductivity has a Drude-like linear density dependence, $\sigma(p) \approx e\mu^*(p - p_0)$, consistent with a two-phase mixture picture where the total conductivity is dominated by mobile carriers with mobility μ^* and density $p - p_0$. The $\sigma(p)$ data at different T further suggest that the resistivity change on the two sides of the non-monotonic $\rho(T)$ of low density 2D systems have distinct origins: one comes from $\mu^*(T)$ and the other is a result of $p_0(T)$. The low T metallic conduction in the degenerate regime is accompanied by a sharply increasing $\mu^*(T)$ as T decreases. On the other hand, the resistivity change of 2DHS in the non-degenerate regime is dominated by a p_0 that decreases rapidly as T increases.

Transport measurements were performed on a 2DHS in two 10nm wide GaAs QW samples similar to the ones used in our previous studies[19, 22, 23]. The samples were grown on (311)A GaAs wafer using $\text{Al}_{1.1}\text{Ga}_{0.9}\text{As}$ barriers and symmetrically placed Si delta-doping layers. The metal backgate used to tune the hole density was about

*Electronic address: xuan.gao@case.edu

0.15mm away from the QW, such that the Coulomb interaction between holes are unscreened by the gate and remains long-range. The samples were prepared in the form of a Hall bar, of approximate dimensions $2 \times 9 \text{ mm}^2$, with diffused In(1%Zn) contacts. The measurement current was applied along the high mobility $[2\bar{3}3]$ direction and kept low such that the power delivered on the sample was less than 3 fWatts/cm^2 to avoid over heating the holes [19].

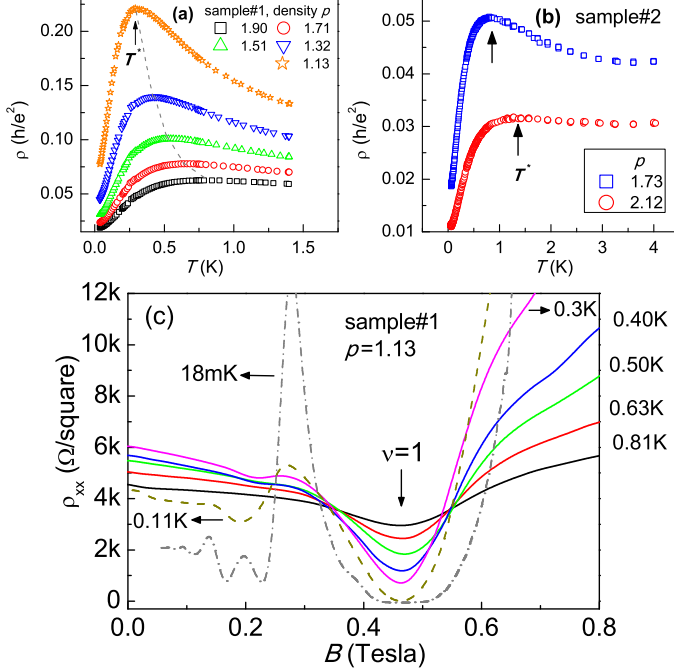


FIG. 1: (color online) (a) Non-monotonic $\rho(T)$ for 2DHS with density ($p=1.90, 1.71, 1.51, 1.32, 1.13$) in a 10nm wide GaAs QW sample #1. The cross-over temperature T^* of the non-monotonic $\rho(T)$ of different p is connected by a dashed line to guide the eye. (b) ρ vs. T for $p=1.73, 2.12$ in sample #2, showing that non-monotonic $\rho(T)$ exists even in the highly conductive regime with ρ as low as $\sim 0.01 \times h/e^2$. (c) Resistivity ρ_{xx} vs. perpendicular magnetic field B at different temperatures for $p=1.13$ in sample #1. For $T > T^*$, the $\rho_{xx}(B)$ curves still exhibit SdH dip at $\nu=1$ whose position does not change with T .

Before we go into the details of the density dependent conductivity data and analysis, we use Fig.1 to establish some basic transport and magneto-transport behavior of the low density 2DHS. Fig.1a presents the temperature dependent resistivity $\rho(T)$ at $B=0$ for several densities ($p=1.90, 1.71, 1.51, 1.32, 1.13$) in sample #1 (the unit for p is $10^{10}/\text{cm}^2$ throughout this paper). For this sample, the MIT happens around $p_c \approx 0.8$ when the density is changed by the back-gate voltage V_g [23]. It can be seen in Fig.1a that $\rho(T)$ changes from metallic ($d\rho/dT > 0$) to insulating-like ($d\rho/dT < 0$) above a characteristic temperature T^* which becomes larger when p increases, consistent with previous findings in literature[15–18]. Thanks to the suppressed phonon

scattering in our narrow QWs compared to wider QWs or heterostructures[16], here we are able to directly observe such non-monotonic $\rho(T)$ into a much lower resistivity regime ($\rho \sim 0.01 \times h/e^2$) than literature, as shown in Fig.1b for $p=2.12$ in sample #2.

The 2D hole density is determined by the positions of Shubnikov-de Haas (SdH) oscillations as $p = \nu \times B_\nu \times e/h$, where ν is the Landau filling factor and B_ν is the perpendicular magnetic field at the corresponding ν . Fig.1c plots the longitudinal magneto-resistivity $\rho_{xx}(B)$ for $p=1.13$ of sample #1 at various temperatures ($T=0.018\text{--}0.81\text{K}$). Throughout this whole temperature range covering both $T < T^*$ and $T > T^*$, SdH oscillation is well established at $\nu=1$ and $B_{\nu=1}$ does not change with temperature, indicating a constant p . In addition, we note that the $\nu=1$ SdH oscillation persists up to at least 0.81K , a temperature comparable to T_F ($=1.0\text{K}$ using effective hole mass $m^*=0.3m_e$ [21]) or the cyclotron energy Δ_c at $\nu=1$. This is surprising since SdH oscillation amplitude should decay strongly above $k_B T \sim 0.1 \times \Delta_c$ according to the Lifshitz-Kosevich formula[24], $\delta\rho_{xx} \propto \frac{2\pi^2 k_B T / \Delta_c}{\sinh(2\pi^2 k_B T / \Delta_c)}$. The fact that SdH is observed at $T > T^*$ points to the non-classical nature of dilute 2DHS with large r_s at these semi-degenerate temperatures.

While a decreasing ρ with T in the regime of $T > T^*$ is expected in several models, either due to interaction/correlation effects [7–9] or classical scattering [12], it has been difficult to identify the exact mechanism[14]. We studied the density dependence of the conductivity σ to gain more insights into the transport mechanism of metallic 2DHS when the temperature coefficient $d\rho/dT$ changes sign at T^* . Fig.2a and b present $\sigma(p)$ for sample #1 and #2 from 0.035K ($T \ll T_F$) up to 4K ($T > T_F$) over the density range $0.7 < p < 2$. A few features in $\sigma(p)$ are salient when the 2DHS crosses over from the low T degenerate (open symbols) to high T semi-degenerate (solid symbols) regime. First, similar to a previous report [25], at low T 's, $\sigma(p)$ turns up sharply around the MIT ($p = p_c$) and then follows a straight line with large slope at $p > p_c$. As T increases, the slope of the linear dependence becomes smaller and at the same time the sharp upturn at $p \sim p_c$ straightens. Eventually at high temperatures, $\sigma(p)$ becomes a linear function over the whole range of p . Yet the slope and intercept of the $\sigma(p)$ data at high T are much smaller than the low T curves. Linear $\sigma(p)$ dependence is expected in Drude model with the slope corresponding to the mobility of carriers. Therefore, the dramatic slope change in $\sigma(p)$ in our data suggests a dramatically enhanced mobility of free carriers at low T . In the Drude model, the finite intercept p_0 of $\sigma(p)$ would correspond to the density of localized carriers, which appears to change with T as indicated by data in Fig.2a and b.

Previously, the low T behavior of $\sigma(p)$ near the critical regime ($p \sim p_c$) was analyzed in terms of the percolation model as $\sigma = A(p - p_c)^\delta$ with $\delta \approx 4/3$ where the MIT is driven by the percolation of itinerant carriers

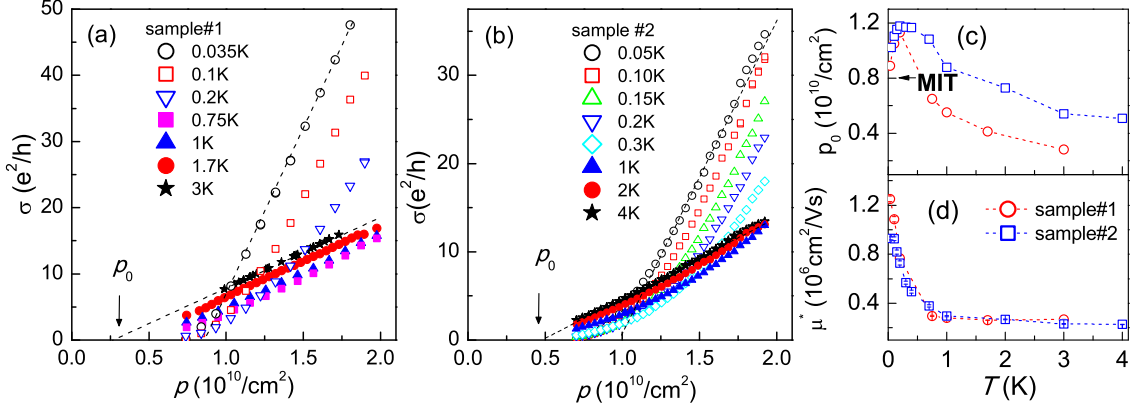


FIG. 2: (color online) (a) The 2D hole conductivity σ plotted as a function of density p at different temperatures for sample #1 (a) and #2 (b). A linear Drude-type function can be used to approximate the conductivity as $\sigma = e\mu^*(p - p_0)$, as denoted by the black dashed lines. (c,d) Fitting parameters p_0 and μ^* plotted against temperature.

with density $p - p_c$ through localized carriers with density p_c [14, 26–28]. A linear relation ($\delta = 1$) between σ and $p - p_c$ at high σ would reconcile the percolation model with the Drude formula when the overall conductivity is dominated by itinerant carriers (i.e. when $\sigma \gg e^2/h$). In that case, the coefficient A in the percolation equation yields the effective mobility μ^* of *itinerant* carriers. Here, we focus on the linear Drude part of $\sigma(p)$ in the high conductivity limit ($\sigma \gg e^2/h$) to examine how the system evolves over a broad range of T . This analysis not only gives a physically meaningful parameter (μ^*), but also works in the high temperature (semi-degenerate) regime where the percolation fit is not applicable. We fit the data in Fig.2a and b with $\sigma > 5e^2/h$ to $\sigma = e\mu^*(p - p_0)$ with μ^* and p_0 as the fitting parameters[29]. The fitted μ^* and p_0 are plotted as a function of T in Fig.2c and d for both samples. First of all, reflecting the metallic transport and rapidly increasing slope of $\sigma(p)$ at low T , μ^* exhibits a sharp upturn at T lower than $\sim 0.5\text{K}$, in contrast to its nearly T -independent behavior at high T . On the other hand, p_0 only shows minor drop at $T < 0.5\text{K}$ but decreases greatly at high T 's (a factor of three/two for sample #1/2). These effects revealed through the *density-dependent* conductivity analysis lead to an important insight on the non-monotonic $\rho(T)$ or $\sigma(T)$ for metallic 2DHS with a *fixed density*: while the metallic conduction in the degenerate regime could be attributed to an enhanced mobility of itinerant carriers, the increasing conductivity in the semi-degenerate regime (i.e. $T > T^*$ in Fig.1) is a consequence of decreased p_0 , or the density of localized carriers, but not a mobility effect. This can actually be inferred directly from the raw data in Fig.2a: as T is lowered from 3K to 0.75K, the $\sigma(p)$ curves stay parallel to each other and shift towards higher intercept (p_0). Within this analysis, one obtains the following picture for the non-monotonic $\rho(T)$ peak around T^* in low density 2D systems: the resistivity drop at $T < T^*$ is due to reduced scattering but the high T ($T > T^*$) resistivity drop comes from a dif-

ferent mechanism where some localized carriers become itinerant and contribute more and more to the overall conductivity when the temperature is increased.

To explain the non-monotonic $\rho(T)$ of low density 2D carrier systems, a few theories involving different mechanisms were proposed [8, 9, 12]. While it is natural that these theories have focused on the effect of temperature on the scattering, diffusion or viscosity of the 2D carriers, our data supply two useful insights that are not contained specifically in the existing theories. First, in the high T semi-degenerate regime, effective mobility μ^* of itinerant carriers (essentially the slope of $d\sigma/dp$) is roughly T -independent and much smaller than the degenerate regime. This emphasizes a distinct transport property of the 2DHS between $T < T^*$ and $T > T^*$: although the 2DHS can have same resistivity value in the degenerate or semi-degenerate regime (Fig.1a), carriers added to the system experience much stronger scatterings/collisions at $T > T^*$ than $T < T^*$. Second, the decreasing ρ in the $T > T^*$ regime is likely tied with the temperature dependence of p_0 , the density of localized carriers, instead of a simple scattering rate effect. These features should be included in future theoretical considerations.

We studied the transverse magneto-resistance or Hall resistance R_{xy} in perpendicular magnetic field to obtain further information on the nature of the two species of carriers inferred from $\sigma(p)$ data. Fig.3a shows R_{xy} vs. B for $p=1.33$ of sample #2 over a broad temperature range ($T=0.1\text{--}4\text{K}$). The data have been symmetrized using both positive and negative field measurements to remove the slight mixing from longitudinal resistance. A grey dashed line is included to show the classical linear Hall resistance $B/(ep)$ according to the hole density p . It is curious to see that the experimentally measured R_{xy} is always smaller than $B/(ep)$, except in the fully developed $\nu=1$ QH state. This significant difference between measured R_{xy} and $B/(ep)$ is quantified in Fig.3b and Fig.3c. Fig.3b shows that $1/eR_H$ is significantly (40-60%) higher than

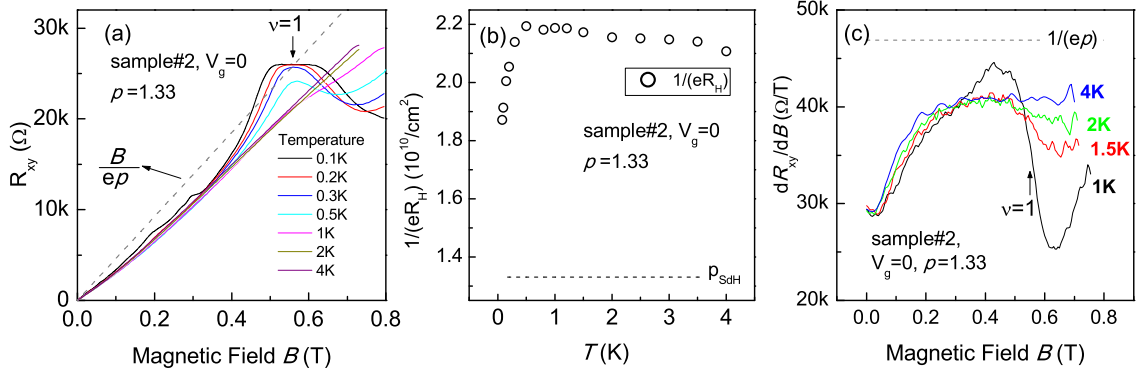


FIG. 3: (color online) (a) Hall resistance R_{xy} as a function of perpendicular magnetic field B for $p=1.33$ in sample #2 at $T=0.1\text{--}4\text{K}$. (b) $1/(eR_H)$ vs. T for $p=1.33$ with R_H as the low field Hall coefficient. (c) Hall slope, dR_{xy}/dB vs. magnetic field at $T=1, 1.5, 2$ and 4K . At high T when the mixing of $\nu=1$ QH effect weakens, the Hall slope shows clear enhancement as B increases.

p . Here, R_H is the Hall coefficient obtained by fitting the slope of $R_{xy}(B)$ at low field ($|B| < 500\text{Gauss}$). It is tempting to relate the temperature dependence of $1/eR_H$ in Fig.3b to a T dependent carrier density effect similar to what we infer from $\sigma(p)$ data. However, two caveats are worth to point out. First, the increase of $1/(eR_H)$ at $T < 1\text{K}$ reproduces previous results on the T -dependent R_H in similar 2DHS[23] whose origin is not fully understood since multiple mechanisms can lead to temperature dependent corrections to R_H [30–32]. The second caution or puzzle one needs to consider is the significant difference between $1/eR_H$ and p : it is as large as 40% even at the lowest temperature studied (80mK). Fig.3c presents the B -dependence of Hall slope dR_{xy}/dB , up to 0.8T . It shows that although dR_{xy}/dB exhibits some increase in B , it is still lower than $1/(ep)$ which is anticipated from density. In conventional two-band transport model, the low field Hall slope dR_{xy}/dB is related to both the density and mobility of the two carrier species as $1/(e \times dR_{xy}/dB) = (p_1\mu_1 + p_2\mu_2)^2 / (p_1\mu_1^2 + p_2\mu_2^2)$, while $1/(e \times dR_{xy}/dB)$ at high fields ($\mu B \gg 1$) equals to the total carrier density $p_1 + p_2$. Thus the standard two band model always expects a smaller Hall slope at high field. We see that the *opposite* trend is exhibited in our 2DHS as dR_{xy}/dB becomes larger at higher B in Fig.3c. We speculate that the increase in Hall slope at high B is caused by the localization or Wigner crystallization of carriers[33]. Because the two carrier species we consider can have both temperature and magnetic field dependent density and mobility, we do not have a reliable model to fit $R_{xy}(B)$ data to compare with the zero field conductivity analysis in Fig.2. One possible implication of the small Hall slope in our experiments is that there exists carriers which contribute to current but not Hall voltage. Obviously, further study is required to understand the anomalous Hall slope and the nature of the two carrier species in 2DHS with large r_s .

It is worthwhile to point out that our results may in fact be compatible with several theories which empha-

size the coexistence of a conducting metallic phase and an insulating localized phase near the MIT [6, 9, 12]. In the micro-emulsion scenario of the 2D MIT, the 2D metallic phase constitutes of mobile Fermi liquids percolating through bubbles of Wigner crystals which have much lower conductivity [9]. The original micro-emulsion model suggested that the $1/T$ -dependent viscosity of correlated electron fluid as the explanation for the decreasing ρ in the high T regime of $T \sim T_F$. Our $\sigma(p)$ data suggest that the continuous melting of Wigner crystal is perhaps more important in the experimentally accessed temperature range here, since only p_0 has strong temperature dependence at $T > T^*$. Thus theoretical calculations on the density dependent conductivity and the Hall effect of micro-emulsion would be desirable to compare further with experiment. In other classical percolation models of the 2D MIT [26–28], the nature and the high temperature fate of the localized carriers have not been addressed theoretically so far. In those theories, more detailed calculations need be done to see if thermal activation of localized carriers can produce the effects reported here.

In summary, we have studied the density dependent conductivity of a 2DHS in GaAs QW as T is raised from the low T degenerate ($T \ll T_F$) to high T semi-degenerate ($T > T_F$) regime. In both regimes, the system's conductivity can be described by a Drude-like formula $\sigma(p) \approx e\mu^*(p - p_0)$ in the high conductivity limit. The temperature dependence of $\sigma(p)$ reveals that the metallic transport at $T < T_F$ is associated with the dramatically enhanced μ^* at low T , while the system's resistivity decrease at $T \sim T_F$ is likely a result of some localized carriers becoming conducting. However, the temperature and magnetic field dependence of Hall resistance requires further understanding.

X.P.A.G. is indebted to G.S. Boebinger, A.P. Mills and A.P. Ramirez for useful suggestions at the early stage of the work, and thanks E. Abrahams, S. Das Sarma, V. Dobrosavljević, S. Kivelson, and B. Spivak for dis-

cussions. This work was supported by NSF (Grant No. DMR-0906415).

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